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A new model for cork weight estimation in Northern Portugal with methodology for construction of confidence intervals

Teresa J.F. Fonseca[a,*], Bernard R. Parresol[b]

[a]Departamento Florestal, Universidade de Trás-os-Montes e Alto Douro, Quinta de Prados, 5001 Vila Real, Portugal
[b]USDA Forest Service, Southern Research Station, P.O. Box 2680, Asheville, NC 28802, USA

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Abstract

Cork, a unique biological material, is a highly valued non-timber forest product. Portugal is the leading producer of cork with 52% of the world production. Tree cork weight models have been developed for Southern Portugal, but there are no representative published models for Northern Portugal. Because cork trees may have a different form between Northern and Southern Portugal, equations developed with southern data do not always predict well in the North. An analysis of eight tree variables revealed the interaction between tree circumference (outside bark at 1.3 m) (CSC) and debarking height (H_{DEB}) to be the best predictor variable. A nonlinear exponential function was chosen over a simple linear function due to a slight curvature exhibited in the plot of weight over CSC $\times$ H_{DEB}. The paper concludes with a section on construction and use of confidence intervals about the mean and individual predictions from the nonlinear regression, plus a method to place bounds on an aggregate estimate for a stand.

Keywords: Cork production; Exponential function; Prediction confidence intervals; *Quercus suber*; Sobreiro

1. Introduction

Bark of the cork oak (*Quercus suber* L.) is used for cork, a unique biological material that is difficult to replace by synthetics. In Portugal cork oak is commonly called "sobreiro", but is also known as "sobro". In Spain it is referred to as "alcornoque" and sometimes as "suro". In France cork oak is called "chêne liège", in German "korkeiche", and in Italian "quercia da sughero" (Rehm, 1994). Cork oaks grow in slightly moist areas with siliceous soils in pre-coastal and coastal regions of Africa and Europe. The natural range covers northern Algeria, Morocco, and Tunisia in Africa; and France (including Corsica), Italy (including Sardinia and Sicily), Portugal, and Spain in Europe (Fig. 1). The species is cultivated in many parts of the world, including the US (Cooke, 1946; Fowells, 1949; Natividade, 1950).

Natural cork is a highly valued renewable resource harvested from the living bark of the cork oak. The major cork producing nations, with data on number of hectares and tonnes of production (Natural Cork Quality Council, 1999), are listed in Table 1. These nations together provide 2,200,000 ha of cork forest. As can be seen in Table 1, Portugal leads the world in cork production (52% of the world's total), harvesting 175,000 t annually.

Cork is used in a variety of products, from construction materials to gaskets, but its most important use is as a stopper for premium wines. Wine corks

* Corresponding author. Tel.: +351-259-350625; fax: +351-259-350480.
E-mail address: tfonseca@utad.pt (T.J.F. Fonseca).

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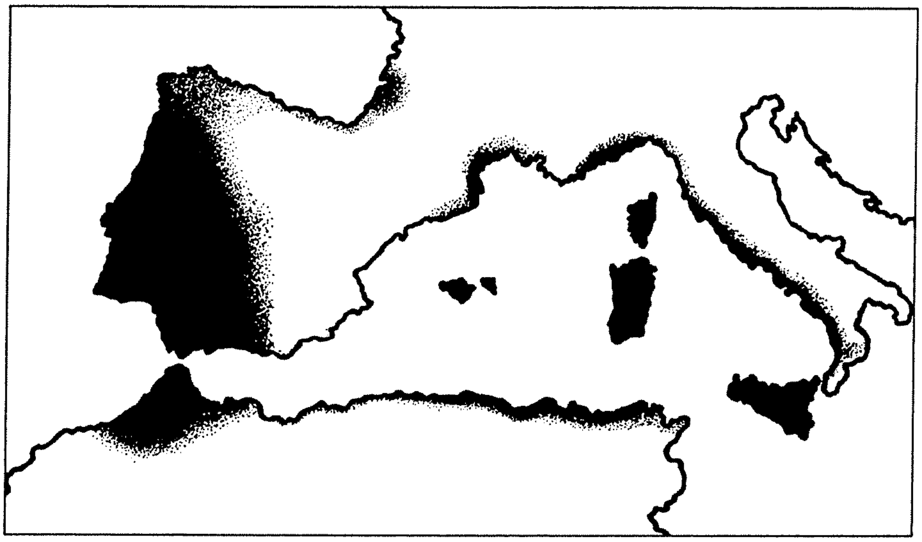

Fig. 1. Natural range of cork oak in Mediterranean and Atlantic areas.

account for approximately 15% of total production by weight and two-thirds of cork revenues (Natural Cork Quality Council, 1999). Table 2 displays a comparison of cork products as measured by revenue generated. Cork products generate approximately 1.5 billion euros in revenue annually (Natural Cork Quality Council, 1999). Thus, natural cork comprises one of the world's most important non-timber forest products.

In Portugal, cork trees are first stripped when they reach a circumference at breast height over bark of 70 cm, typically around age 25. This cork is called "virgin cork", as it is produced by the original phellogen and is of poor industrial quality due to the numerous furrows and cracks caused by the intense radial growth tensions. The new cork layers produced by a regenerated phellogen, known as "second cork", for the same reasons is still of relatively poor quality (Pereira et al., 1987; Gourlay and Pereira, 1997). A 9 year cycle is used for the successive harvests of reproduction cork (called amadia) from the trunk and main branches. The cork is removed from trees between the middle of May to the middle of August when the trees are actively growing, because the new, tender cork cells break easily; thus, the cork comes away easily from the trunk. Harvest difficulties occur if the process is not carried out when the tree is in full growth. If it becomes evident that the cork is being

Table 1
Annual cork production and hectares in cork oak stands of the major cork producing countries

Country	Forest area (ha)	% of world's cork forest area	Production (1000 t)	% of world's production
Portugal	725000	33	175	52
Spain	510000	23	110	32
Italy	225000	10	20	6
France	22000	1	5	1
Morocco	198000	9	15	4
Algeria	460000	21	6	2
Tunisia	60000	3	9	3
Total	2200000	100	340	100

Table 2
The value of the principal cork products generated annually

Industry segment	Value in euros (1000)
Wine stoppers	€1000000
Floor and wall coverings	€300000
Expanded agglomerated cork	€100000
Other products	€100000
Total cork products	€1500000

stripped too early or too late in the season the stripping is usually stopped, a year's delay in cork extraction being preferred to damage to the phloem and cambium of the tree. The harvesting process follows an age old collection method that enables the trees to flourish without the use of herbicides, fertilizers, and irrigation.

The cork industry supports a large agrarian population, but despite its economic importance few models

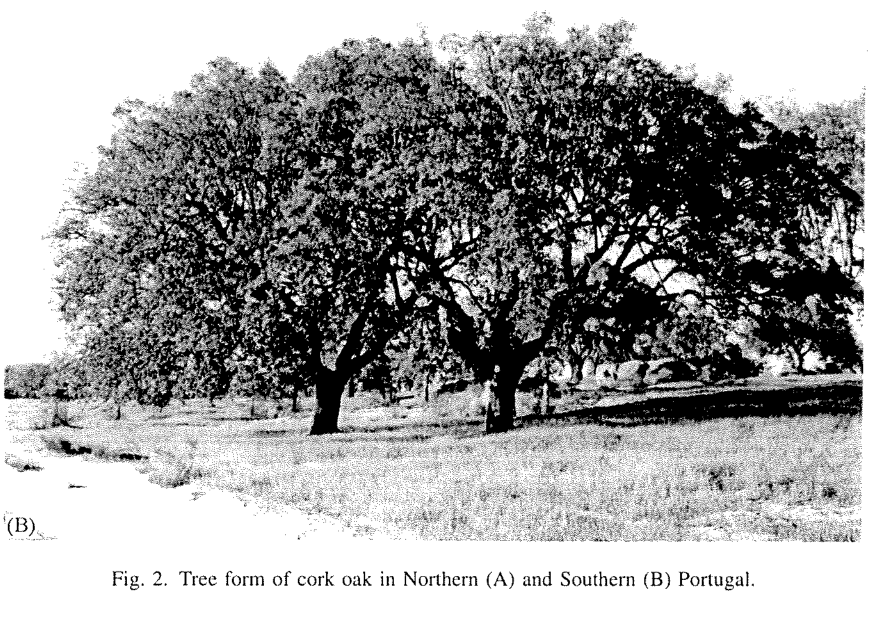

Fig. 2. Tree form of cork oak in Northern (A) and Southern (B) Portugal.

have been developed for estimation of tree cork weight yield. Some of the equations developed (e.g. Natividade, 1950; Guerreiro, 1951; Ferreira et al., 1986) are site specific and do not predict well in other regions due to polymorphism in tree form (Fig. 2(A) and (B)) across the species geographic distribution. This statement is in agreement with the results presented by Ferreira and Oliveira (1991). The authors analyzed the variability of cork oak stands in several regions of Portugal and pointed out that it was not feasible to use a production model at the national level. They noticed that some of the study areas could be grouped, according to the mean tree dimensions, but the study area located on the north part of the country should be considered separately. Hence, there is a need for a new cork weight equation that can aid in the estimation of cork oak production in Northern Portugal. Perhaps as important as the weight predictions are the variances of the predictions for the building of prediction confidence intervals.

2. Data

The data consist of 205 sample trees (amadia cork) from four locations in Northern Portugal (Fig. 3). Data were collected during the growing season, which is the appropriate period for removing cork. Circumference at breast height (1.3 m) before and after the stripping operation (CSC and CBC, respectively) was measured to the nearest 1 cm. The thickness of the bark (B) was calculated through the expression: $B = (\mathrm{CSC} - \mathrm{CBC})/2\pi$.

Trees were measured for height to base of live crown (HBLC) and at the point on the stem where debarking occurred, called debarking height (H_{DEB}). We considered the variable height to base of live crown as the stem height up to the beginning of the crown. Although this length may be very low (the minimum value was found to be 1 m, as shown in Table 3) the average value is usually higher (8.5 m, for our data set) and is easily measured.

When the trees were also debarked on the branches, H_{DEB} was defined as the sum of debarked height on the stem ($H_{\mathrm{DEB\text{-}S}}$) and the length of the debarked sections on the branches ($H_{\mathrm{DEB\text{-}B}}$), that is,

$$H_{\mathrm{DEB}} = \begin{cases} H_{\mathrm{DEB\text{-}S}}, & \text{if debarking occurs only on the stem} \\ H_{\mathrm{DEB\text{-}S}} + \sum_{i=1}^{\mathrm{NB}} H_{\mathrm{DEB\text{-}B}(i)}, & \text{otherwise} \end{cases} \quad (1)$$

where NB represents the number of branches debarked. For 98 of the sample trees, heights (HBLC and H_{DEB}) were measured to the nearest 0.01 m; the other 107 tree heights were measured to the nearest 0.1 m.

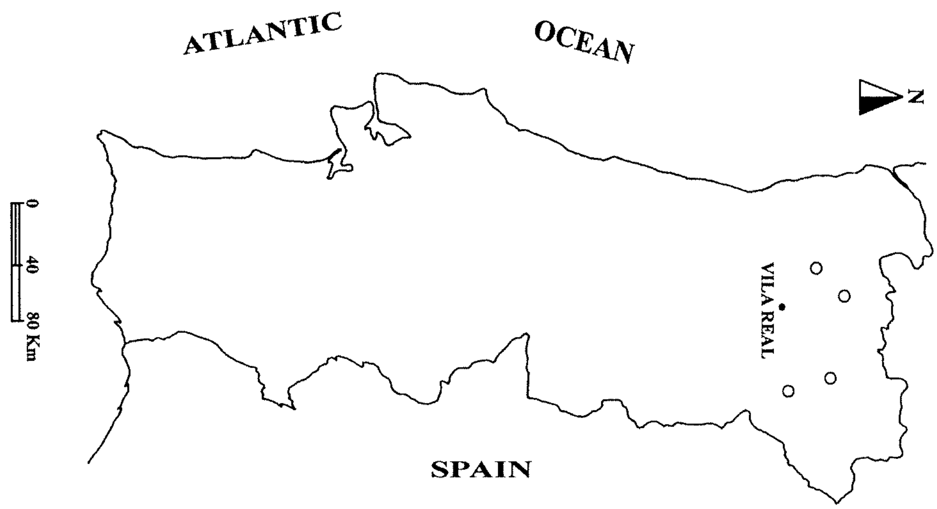

Fig. 3. Locations of the sampled cork oak stands.

Table 3
Summary characteristics of the 205 cork oaks sampled in Northern Portugal[a]

Variables	Minimum	Mean	Maximum	Standard deviation
CSC (cm)	52	104.3	248	28.6
CBC (cm)	43	87.3	223	26.8
B (cm)	1	2.8	5	0.8
H_{DEB} (m)	1.0	3.6	12.0	2.0
HBLC (m)	1.0	8.5	21.0	5.0
NB	0	0.6	6	1.2
CD (m)	2.2	6.0	12.5	1.9
W (kg)	3.0	25.9	160.0	20.6

[a] CSC is tree circumference (1.3 m) outside bark, CBC circumference (1.3 m) under bark, B bark thickness, H_{DEB} debarking height, HBLC height to base of live crown, NB number of branches debarked, CD crown diameter, and W stripped tree cork weight.

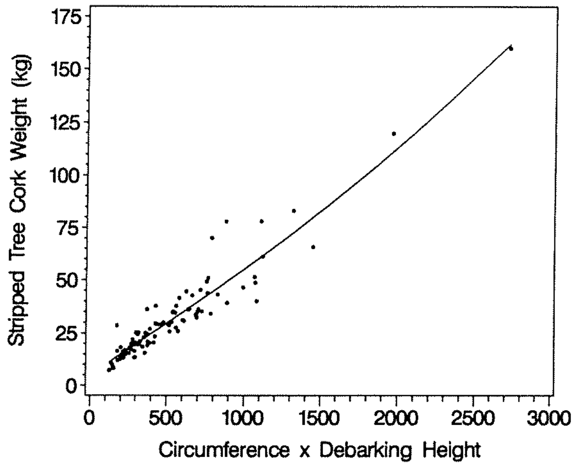

Fig. 4. Scatter plot and response curve of stripped tree cork weight (kg) over the interaction term of tree circumference outside bark (cm) at 1.3 m above ground by debarking height (m).

All the cork boards (reproduction cork) removed from a sample tree were weighed with a precision of either 0.1 kg (98 trees) or 0.5 kg (107 trees). Total green weight of cork (W) per tree was obtained as the sum of the board weights. In addition, crown projection along the four cardinal directions (N, S, E, W) was measured to the nearest 0.1 m in order to calculate the crown diameter (CD) of the tree. The characterization of the data is listed in Table 3.

3. Model

An examination of previous models used for cork weight prediction (Natividade, 1950; Guerreiro, 1951; Ferreira et al., 1986; Montero, 1987) showed CSC, CBC, H_{DEB}, HBLC, B, CD, crown basal area, and stem cross-sectional area to be the most important explanatory variables. Ferreira et al. (1986) and Montero (1987) found the interaction of CSC $\times$ H_{DEB} to work very well. All possible linear regressions were run with the eight tree variables plus the addition of CSC^2, CBC^2, CSC $\times$ H_{DEB} and CBC $\times$ H_{DEB}. The simple interaction term, CSC $\times$ H_{DEB}, accounted for most of the variation in the weight data. Additional terms did not provide any significant improvement. A scatter plot of W over CSC $\times$ H_{DEB} revealed a slight curvilinear trend (Fig. 4), hence, the following exponential model was hypothesized:

$$W = \beta_0 + \beta_1 \exp[(\mathrm{CSC} \times H_{\mathrm{DEB}})^{\beta_2}] + \varepsilon \qquad (2)$$

where the β's are model parameters and ε is residual error. This model was fitted to the data using nonlinear least squares regression and a test of coefficients showed the β_0 parameter to be non-significant. An examination of the residuals showed only a weak heteroscedastic trend. A multiplicative error model was fitted to the residuals using the techniques outlined in Parresol (1993), but showed no significance, hence weighted regression was deemed unnecessary. After removing the intercept parameter and refitting, the following function resulted:

$$\hat{W} = 0.6183 \exp[(\mathrm{CSC} \times H_{\mathrm{DEB}})^{0.2183}] \qquad (3)$$

This equation explained 86% ($R^2 = 0.864$)[1] of the variation in observed weight values with a mean square error of 57.95 kg^2.

4. Application and reliability

Knowing the prediction interval is as critical a knowledge as the point estimate of tree cork weight. The construction of simple and joint confidence

[1] As recommended by Kvålseth (1985) for nonlinear regression, we used $R^2 = 1 - \sum(W - \hat{W})^2 / \sum(W - \overline{W})^2$.

intervals about nonlinear regressions is analogous to that of linear regressions using a matrix algebra approach. Two quantities are needed to construct the bounds on the predictions: (1) the standard errors of the predictions (S.E.) and (2) a B-value, where $B = t(1 - \alpha/2g; n - p)$ is the Bonferroni value for simultaneous prediction limits, α is the Type I error rate set by the user, g the number of predictions being made, p the number of equation coefficients ($p = 2$ in our case), and n the number of regression observations ($n = 205$ in our case). The interval boundary points are obtained from

$$\hat{W} \pm \text{S.E.}(B) \tag{4}$$

For a discussion of Bonferroni bounds, see Neter et al. (1985).

4.1. Leverage and standard errors

To calculate a standard error we must first compute a value known as the leverage. The regression design matrix X (205 × 2) is formed by differentiating W with respect to the β's, that is, $X = \partial W/\partial\beta$. For the ith observation, a scaler known as the leverage is computed as follows:

$$l_i = \boldsymbol{x}_i(\boldsymbol{X}'\boldsymbol{X})^{-1}\boldsymbol{x}_i' \tag{5}$$

where $\boldsymbol{x}_i$ is the ith row vector of $\boldsymbol{X}$ and $\boldsymbol{X}'$ is the transpose of $\boldsymbol{X}$. There are several types of standard errors, the two most important being (1) for the predicted mean value of W_i, $s(\hat{W}_i)$ and (2) for a predicted value of an individual (new) outcome drawn from the distribution of W_i, $s(\hat{W}_{i(\text{new})})$. They are calculated as

$$s(\hat{W}_i) = \sqrt{l_i s^2} \tag{6a}$$

$$s(\hat{W}_{i(\text{new})}) = \sqrt{l_i s^2 + s^2} \tag{6b}$$

where s^2 is the mean square error of the regression.

4.2. Design vector and covariance matrix

The vector $\boldsymbol{x}_i'$ for Eq. (5) has the form

$$\begin{bmatrix} \exp[(\text{CSC}_i \times H_{\text{DEB}(i)})^{0.2183}] \\ 0.6183\exp[(\text{CSC}_i \times H_{\text{DEB}(i)})^{0.2183}](\text{CSC}_i \times H_{\text{DEB}(i)})^{0.2183}\ln(\text{CSC}_i \times H_{\text{DEB}(i)}) \end{bmatrix} \tag{7}$$

The computed $(\boldsymbol{X}'\boldsymbol{X})^{-1}$ matrix for use in Eq. (5) is

$$\begin{bmatrix} 2.613\times10^{-5} & -1.300\times10^{-6} \\ -1.300\times10^{-6} & 6.945\times10^{-8} \end{bmatrix} \tag{8}$$

The mean square error of Eq. (3), as already given, is 57.95. With these three pieces of information, bounds can be computed for the cork weight predictions from Eq. (3).

4.3. Calculations

The following examples serve to illustrate the use of Eq. (3) and the method of constructing confidence intervals. Consider a tree with a circumference at 1.3 m of 100 cm and debarking height of 4.25 m. Using Eq. (3) the cork weight is estimated as

$$\hat{W} = 0.6183\exp[425^{0.2183}] = 26.23\ \text{kg} \tag{9}$$

Inserting the values 100 for CSC and 4.25 for H_{DEB} into Eq. (7) and transposing (to get the row vector $\boldsymbol{x}$) we obtain

$$[42.43 \quad 595.0] \tag{10}$$

The leverage is calculated from Eq. (5) as follows:

$$\begin{aligned} l &= [42.43 \quad 595.0] \\ &\times \begin{bmatrix} 2.613\times10^{-5} & -1.300\times10^{-6} \\ -1.300\times10^{-6} & 6.945\times10^{-8} \end{bmatrix} \begin{bmatrix} 42.43 \\ 595.0 \end{bmatrix} \\ &= 0.005988 \end{aligned} \tag{11}$$

From Eqs. (6a) and (6b) the standard errors are

$$s(\hat{W}) = \sqrt{(0.005988)(57.95)} = 0.5891 \tag{12a}$$

$$s(\hat{W}_{\text{new}}) = \sqrt{(0.005988)(57.95) + 57.95} = 7.635 \tag{12b}$$

The 95% B-value is $t(1 - 0.05/2; 203) = t(0.975; 203) = 1.972$. From Eq. (4) the overall mean prediction confidence interval and individual prediction confidence interval are

$$26.23 \pm 0.5891(1.972) = 25.1 \le \hat{W} \le 27.4 \tag{13a}$$

$$26.23 \pm 7.635(1.972) = 11.2 \le \hat{W}_{\text{new}} \le 41.3 \tag{13b}$$

Suppose from a small cork oak stand we have three trees with circumference and debarking height values of 85 cm and 3.22 m, 140 cm and 4.47 m, and 210 cm and 9.35 m. Using Eq. (3) weights are estimated as

$$\hat{W}_1 = 0.6183\exp[273.7^{0.2183}] = 18.61\,\text{kg} \quad (14a)$$

$$\hat{W}_2 = 0.6183\exp[625.8^{0.2183}] = 36.50\,\text{kg} \quad (14b)$$

$$\hat{W}_3 = 0.6183\exp[1963.5^{0.2183}] = 116.0\,\text{kg} \quad (14c)$$

Inserting the appropriate values into Eq. (7) and transposing into $\boldsymbol{x}_i$, for $i = 1$ to 3, and stacking the three row vectors into a matrix, we obtain

$$\begin{bmatrix} 30.10 & 355.6 \\ 59.04 & 958.5 \\ 187.6 & 4604 \end{bmatrix} \quad (15)$$

By using this matrix in Eq. (5) instead of the individual vectors $\boldsymbol{x}_i$, a leverage matrix is calculated whose diagonal elements are the leverage values. This averts the need for repetitive calculation of Eq. (5) for each observation. The leverage matrix is

$$\begin{aligned} l_{\text{matrix}} &= \begin{bmatrix} 30.10 & 355.6 \\ 59.04 & 958.5 \\ 187.6 & 4604 \end{bmatrix} \\ &\times \begin{bmatrix} 2.613\times10^{-5} & -1.300\times10^{-6} \\ -1.300\times10^{-6} & 6.945\times10^{-8} \end{bmatrix} \\ &\times \begin{bmatrix} 30.10 & 59.04 & 187.6 \\ 355.6 & 958.5 & 4604 \end{bmatrix} \\ &= \begin{bmatrix} 0.004627 & 0.005307 & -0.005624 \\ 0.005307 & 0.007751 & 0.008775 \\ -0.005624 & 0.008775 & 0.146080 \end{bmatrix} \end{aligned} \quad (16)$$

The individual leverage values are as follows: $l_1 = 0.004627, l_2 = 0.007751, l_3 = 0.1461$. From Eq. (6b), the standard errors for each individual prediction are

$$s(\hat{W}_{1(\text{new})}) = \sqrt{(0.004627)(57.95) + 57.95} = 7.630 \quad (17a)$$

$$s(\hat{W}_{2(\text{new})}) = \sqrt{(0.007751)(57.95) + 57.95} = 7.642 \quad (17b)$$

$$s(\hat{W}_{3(\text{new})}) = \sqrt{(0.1461)(57.95) + 57.95} = 8.150 \quad (17c)$$

For 90% joint confidence intervals about these three predictions, the B-value is $t(1 - 0.10/2(3); 203) = t(0.983; 203) = 2.135$. Using Eq. (4) the joint or simultaneous prediction confidence intervals are

$$18.61 \pm 7.630(2.135) = 2.3 \le \hat{W}_{1(\text{new})} \le 34.9 \quad (18a)$$

$$36.50 \pm 7.642(2.135) = 20.2 \le \hat{W}_{2(\text{new})} \le 52.8 \quad (18b)$$

$$116.0 \pm 8.150(2.135) = 98.6 \le \hat{W}_{3(\text{new})} \le 133.4 \quad (18c)$$

Most likely users of this new model will want an aggregate stand total and bounds on the estimated total cork yield. This is easily accomplished. One can simply sum the predicted cork weight values from the trees in the stand to obtained an estimated total stand yield, that is, $\hat{W}_{\text{total}} = \sum_{i=1}^{T}\hat{W}_i$ where T is number of trees in the stand ready to be stripped. Reliability (i.e. a confidence interval) of the total cork prediction can be determined from variance properties of linear combinations: $\text{Var}(\hat{W}_{\text{total}}) = \sum_{i=1}^{T}\text{Var}(\hat{W}_{i(\text{new})}) + 2\sum_{i<j}\sum\text{Cov}(\hat{W}_{i(\text{new})}, \hat{W}_{j(\text{new})})$. Because the trees are independent, the covariance terms vanish and we are left with

$$\begin{aligned} \text{Var}(\hat{W}_{\text{total}}) &= \sum_{i=1}^{T}\text{Var}(W_{i(\text{new})}) \\ &= (l_1 s^2 + s^2) + (l_2 s^2 + s^2) \quad + \cdots \\ &\quad + (l_T s^2 + s^2) = s^2\sum_{i=1}^{T} l_i + Ts^2 \end{aligned} \quad (19)$$

To illustrate, consider the 20 trees in Table 4. Using Eq. (3) a yield was estimated for each tree and from Eq. (5) a leverage value was computed. From Table 4 we find the sum of the 20 cork tree bark weights to be 617.5 kg and the sum of the leverage values to be 0.1423. Using the square root of Eq. (19), we compute the standard error of the total yield as

$$s(\hat{W}_{\text{total}}) = \sqrt{(57.95)(0.1423) + (20)(57.95)} = 34.16 \quad (20)$$

For an 80% confidence interval about $\hat{W}_{\text{total}}$, the B-value is $t(1 - 0.20/2; 203) = t(0.90; 203) = 1.286$. Using Eq. (4) the prediction confidence interval for the total yield is

$$617.5 \pm 34.16(1.286) = 573.6 \le \hat{W}_{\text{total}} \le 661.4 \quad (21)$$

Table 4
Twenty cork oak trees from a small stand in Northern Portugal[a]

Tree	CSC_i (cm)	$H_{DEB(i)}$ (m)	$\hat{W}_i$ (kg)	l_i
1	75	3.7	18.80	0.004666
2	76	3.5	18.22	0.004548
3	79	6.5	30.72	0.006714
4	80	4.4	22.56	0.005370
5	87	4.0	22.35	0.005335
6	89	5.0	27.24	0.006151
7	90	3.5	20.69	0.005033
8	91	4.5	25.45	0.005860
9	92	5.5	30.34	0.006651
10	95	5.2	29.73	0.006552
11	100	5.2	31.06	0.006769
12	105	4.5	28.64	0.006375
13	108	4.5	29.32	0.006486
14	110	4.2	28.11	0.006290
15	120	6.0	41.43	0.008877
16	127	5.0	36.98	0.007848
17	138	2.5	22.20	0.005308
18	160	6.2	56.19	0.014990
19	165	5.3	49.72	0.011666
20	182	4.6	47.70	0.010854
Totals			617.45	0.142343

[a] CSC is tree circumference outside bark at 1.3 m above ground, H_{DEB} debarking height, $\hat{W}$ estimated cork yield from Eq. (3), and l the leverage value calculated from Eq. (5). See text for details.

From this calculation we are 80% confident that the true total cork yield for this stand of 20 trees will fall between 574 and 661 kg.

5. Discussion

Of the set of variables used in this study, the measure of the stripping surface, given by the interaction term CSC × H_{DEB}, was the best to estimate the cork weight. This result matches that obtained by other authors (e.g. Ferreira et al., 1986; Montero, 1987; Ferreira and Oliveira, 1991; Montero et al., 1996), although some of them determined the H_{DEB} as the debarked length on the stem plus only one length (the maximum value) of the debarked branches. In this study the H_{DEB} is more accurately related with the surface of bark stripping because it refers to total debarking height. In spite of the differences in computation it seems that the variables H_{DEB} and CSC are very stable in predicting the cork weight of the trees across different ecological regions.

Users of this new model should bear in mind that a regression function provides a point estimate which has a variance. When evaluating a group of trees, constructing simultaneous (Bonferroni) prediction confidence intervals on the $\hat{W}_{i(\text{new})}$'s will provide bounds on the estimates with a $1 - \alpha$ family confidence coefficient. Estimation of a stand total cork yield is a straight forward summation of the predictions of the individual trees. A confidence interval on the total yield is easily constructed as was illustrated. This has important implications for economic planning since the quality of information is a critical element for the management of this highly valued resource.

6. Conclusions

The value of cork and the dependence of agrarian populations on income derived from cork production point to the need for accurate forecasting. Variability in tree form between different ecological areas may require separate equations for accurate predictions. As there is a paucity of equations for the north part of the country, a new model has been developed for cork yield estimation in Northern Portugal. Only two measures per tree are needed, circumference at breast height and debarking height, to make predictions.

A shortcoming of the different models that have been published is little information about prediction confidence intervals. The techniques outlined here allow the users to predict productivity for a nine year production cycle on cork oak forests in Northern Portugal and to assess confidence intervals on the predictions.

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